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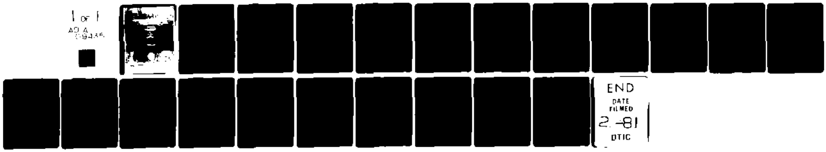

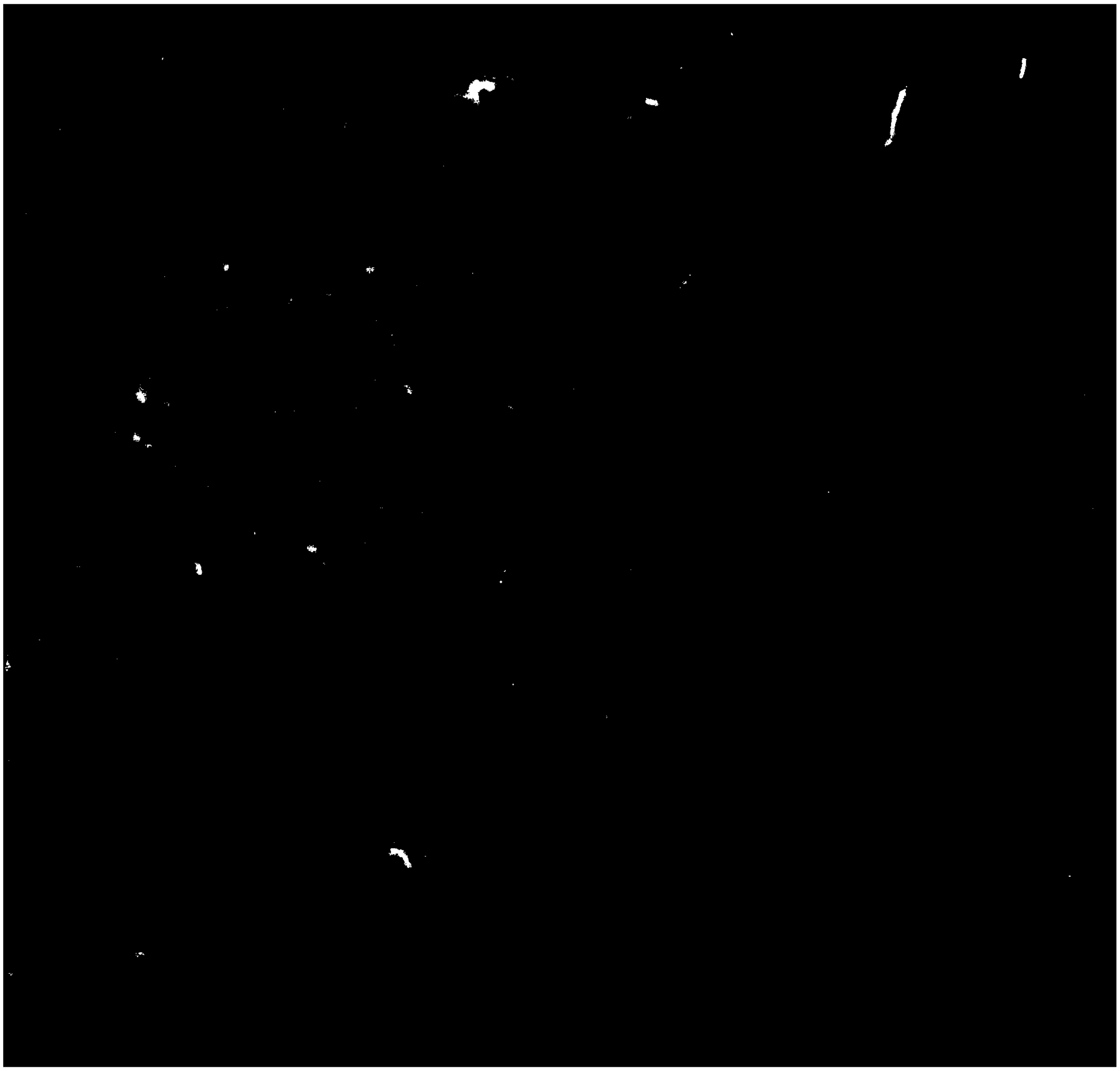

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An experiment in which the enhancement of the efficiency of gyrotron oscillators through profiling of the magnetic field at the cavity is discussed. Electronic efficiencies to 65 percent were obtained, with power levels of 1-100 kW at 35 GHz. Satisfactory agreement with theory was found.

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EXPERIMENTAL EXAMINATION OF THE ENHANCEMENT OF GYROTRON EFFICIENCIES BY USE OF PROFILED MAGNETIC FIELDS

Introduction

The gyrotron has become a very promising source for high power mm wave radiation. To date with gyrotron oscillators (gyromonotrons) a power of 212 kW has been obtained on a CW basis at 28 GHz[1], and 1 MW on a pulsed basis at 100 GHz.[2] Extrapolations to CW Megawatt operation at $\gtrsim$ 100 GHz appear possible.[3] For the primary application presently foreseen for this type of device (electron cyclotron heating in magnetically confined fusion devices),[4,5] efficiency will be of critical importance. Present devices appear to be limited to efficiencies of less than 50% even with the use of tapered cavity walls.[1,2] Recently methods have been proposed for increasing the efficiency to ~70% through profiling of the magnetic field impressed on the cavity. One method utilizes a stepwise profile[6] the other a linear profile.[7] Both methods predict comparable efficiencies, but the latter appears to be more readily realized in practice. We report in this paper a series of experiments which verify the latter theory.

Description of the Experiment

The experiments were performed at a frequency of 35 GHz, using the apparatus shown in Figure 1. The configuration was similar, with the exception of the provisions for tapering the magnetic field, to other gyrotron oscillators.[1,8] The cavity was right circular, and supported the TE_{011} (circular) mode. In order to thoroughly examine the theory, four cavities of different lengths[6] were tried in the experiments. Their parameters are shown in table 1.

The electron gun used had a nominal operating voltage of 70 kV, producing a monoenergetic beam with a theoretically predicted[9] perpendicular to parallel velocity ratio (α) of 1.5 - 1.8. We note that only the energy associated with electron motion perpendicular to the magnetic field is accessible for transfer to the output waves. Therefore, α will determine the ultimate maximum efficiency. For $\alpha = 1.8$, the maximum efficiency achievable is 63 percent.[7]

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Measurement of the output power was performed by converting the TE_{01} circular output into the TE_{10} rectangular mode, employing a commercial mode transducer,[10] and using a calibrated directional coupler and precision attenuator to reduce the power level to where it could be sensed with a calibrated crystal. This method has been previously checked using a calorimeter, and found to be accurate to $\pm$ 5%. The frequency was measured using a conventional wavemeter.

The main (unperturbed) applied magnetic field was produced by a system of superconducting solenoids, and on axis had a profile as shown in figure 1. The unperturbed field over the length of the cavity was uniform to better than $\pm$ 0.5%.

The profiling of the applied magnetic field in the cavity region was accomplished by either shaped collars of steel (figure 2) or active coils. (The collars were used for the short cavities where strong gradients were required). Typical field perturbations produced by these methods are shown in figures 2 and 3. (The profile shown in figure 3 was produced by a coil in which the direction of winding was reversed at the center). For most of the experiments the total applied magnetic field in the cavity region increases approximately linearly along the direction of the electron beam propagation.

<u>Calculation of the Electronic Efficiency</u>

In order to compare unambiguously with the theory, which assumes the RF field profile of a closed end cavity, the reflection at the output end of the cavity was made large, resulting in a relatively large output Q and consequently low radiated power. Thus ohmic losses in the circuit become substantial factors in inferring the electronic efficiency (η_e), defined as the fraction of beam power deposited to the wave, from the measured efficiency (η_m), defined as the ratio of the measured wave power to the beam power. Since the measured power is the deposited power less the circuit losses, we may write

$$\eta_e = \eta_m \left[A(1 - \frac{Q_L}{Q_\Omega})\right]^{-1}$$

where η_m is the measured value of the output power normalized to the beam power. Q_L is the loaded (total) Q, Q_Ω is the ohmic Q of the cavity and A accounts for the loss in the output guide mode converter. A was determined by measurement to be $\simeq 0.8$, and typically η_m/η_e ranged from approximately 0.5 to .7 depending on the cavity used.

Results

All of the cavities oscillated in the TE_{011} mode, identifiable by the frequency of the radiation. The nearest competing mode was found in the longest cavity, where the frequency of the TE_{012} mode was found to be 35.13 GHz, as apposed to 34.97 GHz for TE_{011}.

Of primary interest was the behavior of the efficiency as a function of $\Delta B/B$, defined as the percent increase in B over the length of the cavity. This is shown in figure 3, along with the theoretically predicted behavior. The following observations can be made: (1) Electronic efficiencies of up to 65% were obtained, (2) Enhancements of the efficiency and power (from the uniform field cases) of up to 1.9 were obtained and (3) The agreement of experiment and theory is good for $\Delta B/B. \lesssim 7\%$.

The reason for the fall-off of the efficiency prematurely with $\Delta B/B$ (evident for the shorter cavities) is most likely caused by a degradation in the electron beam due to the influence on the electron gun of the residual fields from the taper producing coils or iron pieces. The influence of small (on the order of one percent) changes in the gun fields cannot be simply predicted, as the electron beam parameters are complicated functions of these fields. Studies are in progress to examine the problem. Restraints on the length of the distance from the cavity to the gun made it impossible to reduce the fields

at the gun in the present experiment. These restraints do not appear to be fundamental, and should be able to be eliminated in future designs.

There has been some conjecture that a field profile with negative slope also produce an enhancement of efficiency, since the change in field could potentially restore losses of coherence between the beam and waveguide modes caused by reduction in the beam energy as it transverses the cavity. (The coherence is given by $\omega - k_{11} \cdot \upsilon_{11} - \frac{\Omega_c}{\gamma}$, where k_{11} is the axial wave number, υ_{11} the axial electron velocity, Ω_c the classical cyclotron frequency, and γ the relativistic mass factor). However, our calculations indicated little support for this conjecture. Subsequent experiments also indicate only slight improvement in the efficiency with this type of profile.

During the experiments another phenomenon, of use in understanding the basic physics of the cyclotron maser, was observed. The effect is illustrated in a plot of efficiency versus beam current for the cavity with $L/\lambda = 9.2$. (Fig.5) Both the experimental points and theoretical curves are given. Qualitative agreement between theory and experiment is evident. Initial investigations indicate that the lack of good quantitative agreement in the magnitude of the efficiency for currents >>0.1A is due to velocity spread on the beam. Both theory and experiment show the efficiency as a double peaked function of the current. This is apparently due to the trapping of the electron bunches, a phenomenon predicted by Sprangle and Drobot.[11] Trapping is the dominant limit on the efficiency of the cyclotron maser. It occurs as the RF fields become strong enough to "pull" some of the electrons out of the phase where they give up energy to the wave. With further increased RF fields (produced by increased beam current) the electrons undergo a 360 degree phase change as they traverse the cavity and, subsequently, a substantial fraction of their energy is transferred to the waveguide mode. This is shown more clearly in figures 6 a, b, and c. These figures are computer calculated plots of the

average electron energy loss (normalized to the initial electron energy) as a group of electrons traverses a cavity with predetermined RF fields. The value of this normalized loss at the end of the cavity is then the efficiency. Figure 6a is for the case for I = 0.1 amperes, while 6b is for I = 1.0a, and 6c for I = 1.5a. For I = 0.1a, we note that the energy loss is monotonic as the particles drift through the cavity. Trapping occurs at the end of the cavity. At I = 1.0a, the Rf fields are stronger, and trapping occurs earlier, causing some of the electrons to regain energy. The resulting efficiency is therefore much lower. At I = 1.5a, the Rf fields are strong enough such that the electrons go through a complete cycle - losing, gaining, then losing again their energy. The resulting efficiency is similar to that with I = 0.1a.

This is the first time that this phenomenon has been reported in the cyclotron maser oscillator, and appears to confirm an important element of the theory which explains the saturation mechanism for this instability.

Comments

For the cavities with $L/\lambda = 7.3$, and $L/\lambda = 9.2$, we note that the 65 percent overall (electronic) efficiency means that, with an α of 1.8, 85 percent of the power in the beam available to the interaction has been extracted. (Only the power associated with the perpendicular motion of the electrons is accessible).[11] Further improvement in the efficiency can come from improving this figure, or by increasing the velocity ratio (α). Refinement of the magnetic profile may help to achieve the former. As to the latter, the present state of the art in gun design appears to yield $\alpha \approx 2$.[9,12,13] If guns with an α of 2.5 can be produced, calculations[7] show that a gyrotron with an efficiency of 78 percent should be possible.

The cavities used in this study produced relatively low powers (1-100 kW), due to the large output Q chosen. In order to produce substantially higher powers, it will be necessary to use lower output Q's and/or higher order cavity modes.[3,7] Both of these methods can reduce cavity losses to the order of a

few percent of the output power. Studies of these methods are currently in progress.

The usefulness of magnetic tapering for efficiency enhancement at higher frequencies will be limited by the field gradients that can be produced. The required gradient, dB/dz, scales as f^2 (assuming operation at the fundamental cyclotron frequency). For high power devices, cavity lengths on the order of $L/\lambda = 5$ are desirable.(3) The 10% value for $\Delta B/B$ which appears to be necessary requires a gradient of 300 Gauss/cm at 35 GHz, and 3.0 kG/cm at 110 GHz. Gradients to approximately 3-5 kG/cm appear feasible with present generation superconducting magnets. Therefore, the use of this method appears feasible in the frequency regime of interest for many fusion devices. The method can be used at even higher frequencies if cyclotron harmonic interaction(14) is employed since the magnetic field required for these cases is reduced by the inverse of the harmonic number.

Conclusions

We have shown that magnetic field profiling can enhance the efficiency by a factor of 1.5 - 1.9. As a result, an electronic efficiency of 65% has been demonstrated, the highest gyrotron efficiency reported so far. The method should be feasible to frequencies of 110-150 GHz for the first cyclotron harmonic and 220-300 GHz for the second cyclotron harmonic, using presently available superconductor magnet technology. The increases observed should be applicable to existing devices, and such use should be able to achieve substantial increases of 1.5 to 1.9 in both their efficiency and power.

It is expected that this method can be extended to higher power devices by use of lower Q cavities and higher order modes.

Acknowledgements

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TABLE 1

CAVITY PARAMETERS (λ = 8.57mm)

L/λ	Measured Total Q
3.3	2000
4.9	2900,650
7.3	1300
9.2	3500

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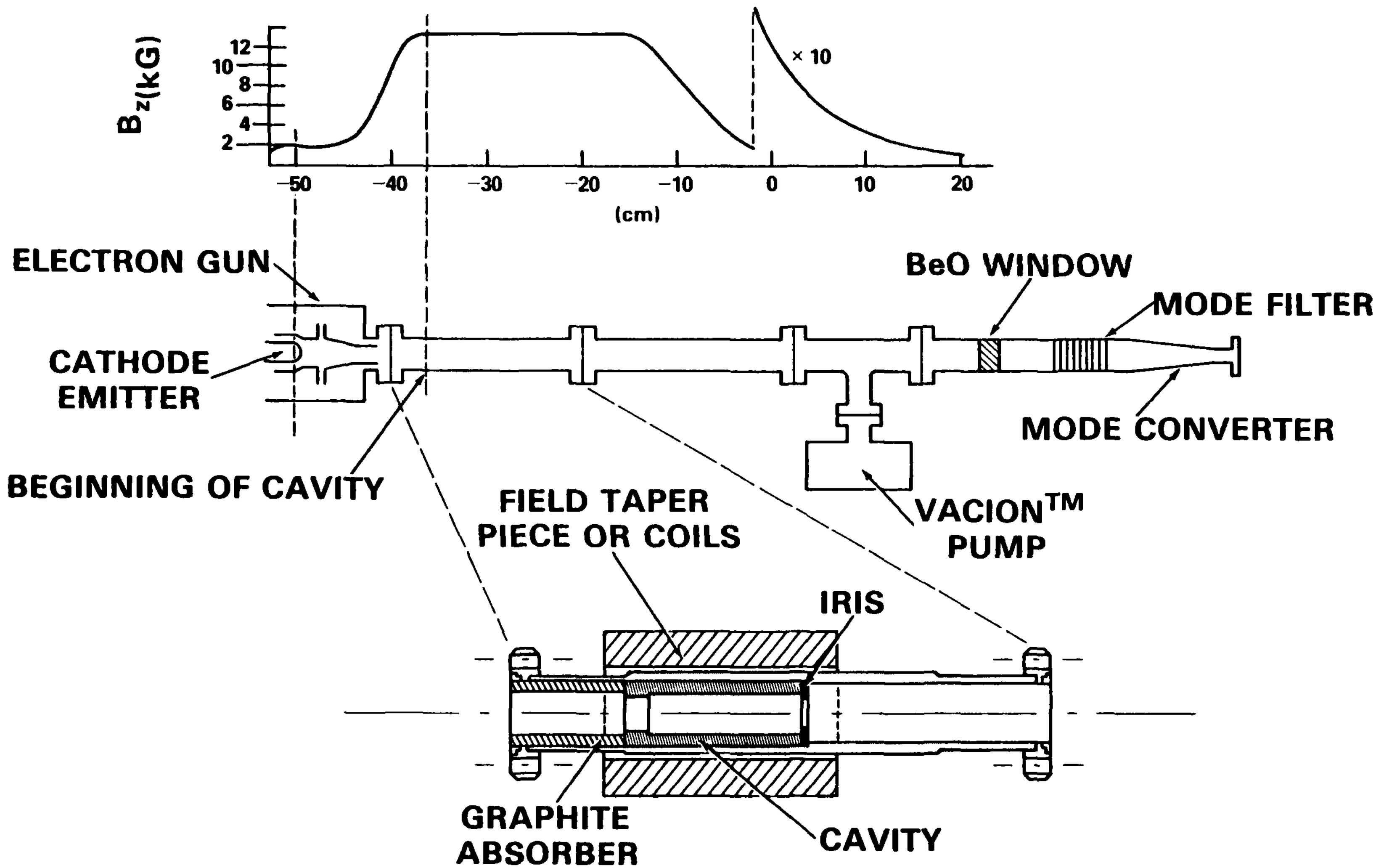

Fig. 1 — Apparatus of the experiment

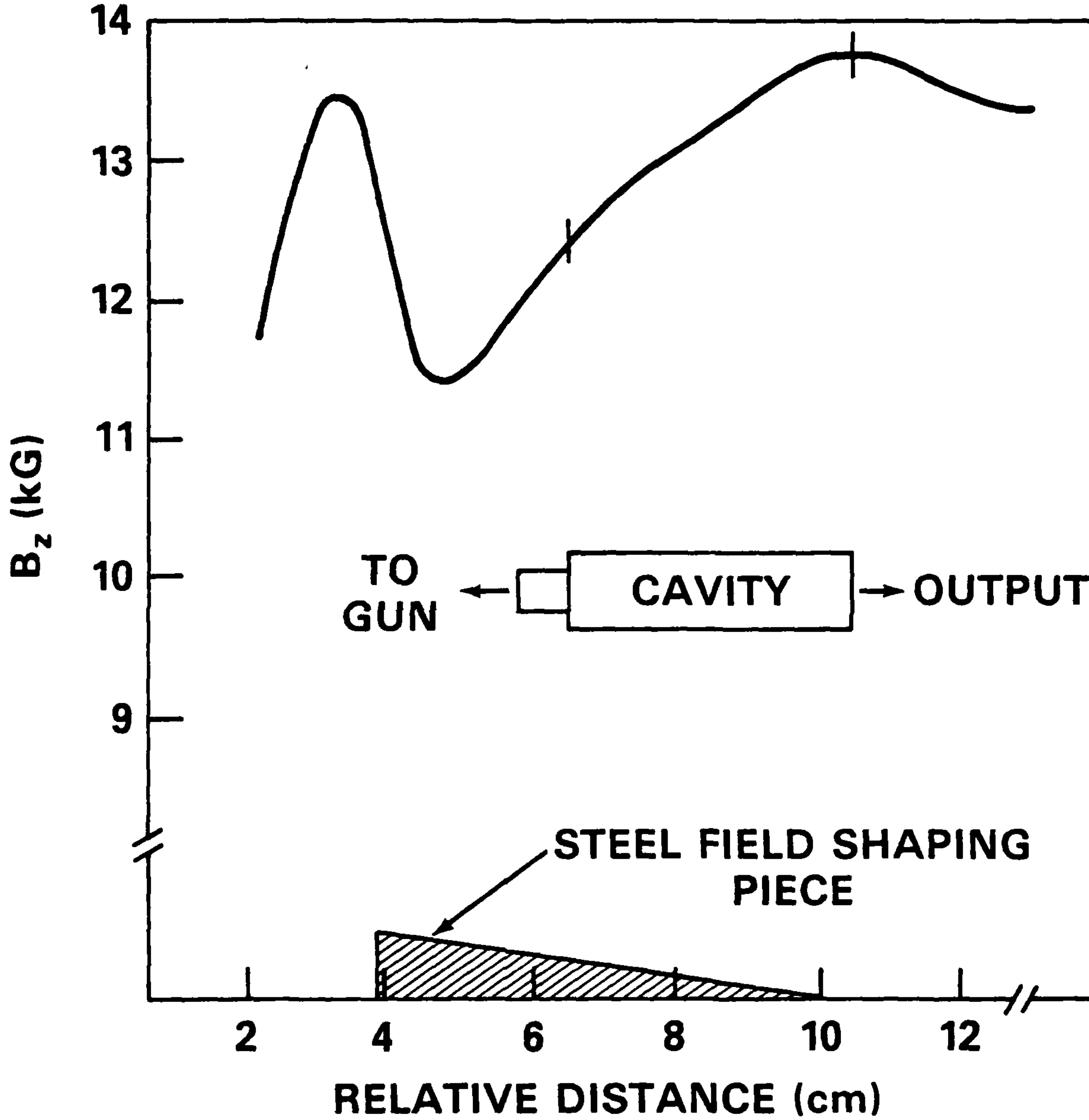

Fig. 2 — Drawing of the field shaping steel collar and the magnetic field resulting from its insertion in the field of the superconducting magnet

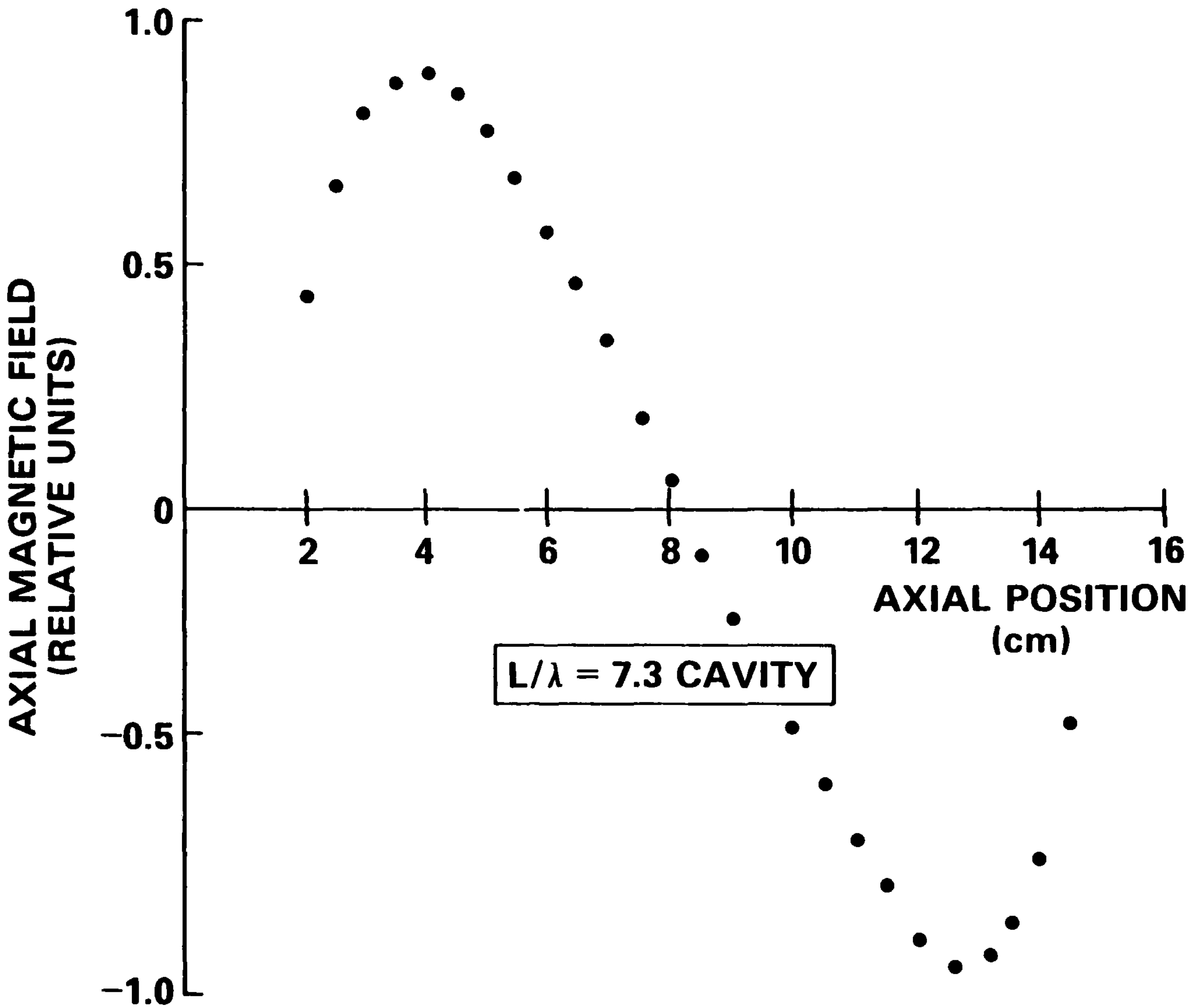

Fig. 3 — Field perturbation produced by the active coils. The coils comprised a solenoid in which the current reversed at the center.

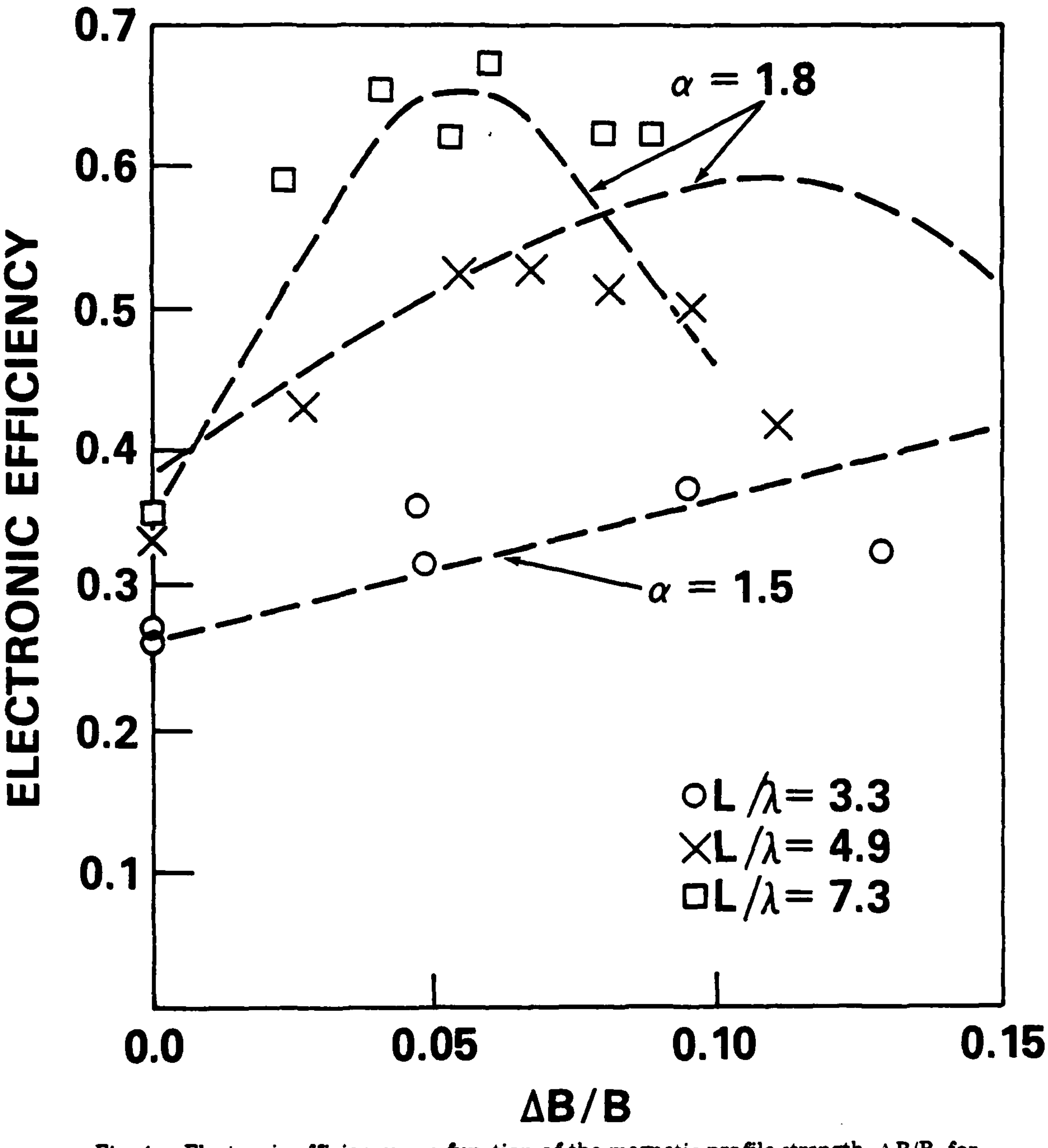

Fig. 4 — Electronic efficiency as a function of the magnetic profile strength, $\Delta B/B$, for those cavities of different length L. λ = 8.6 mm.

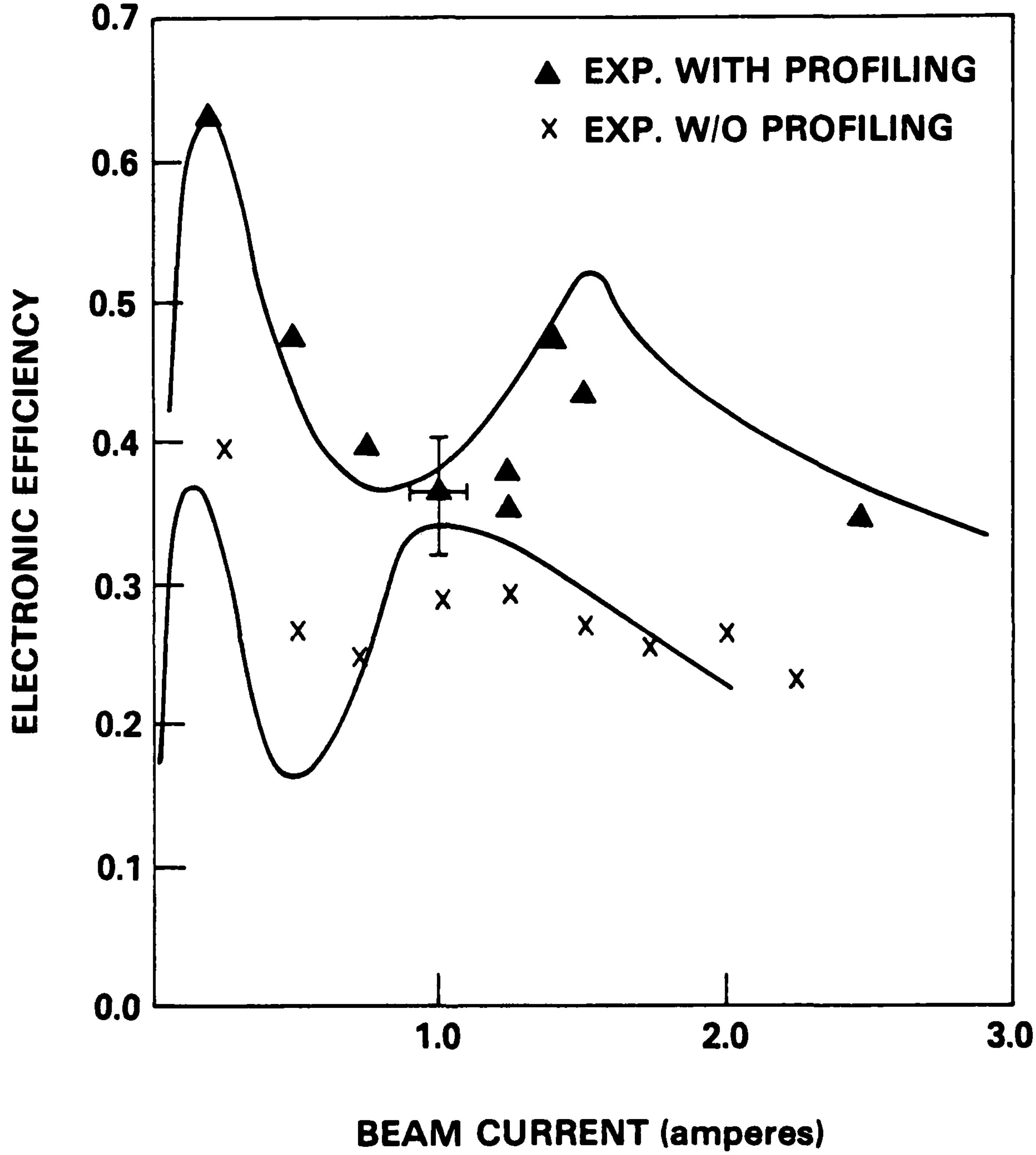

Fig. 5 — Electronic efficiency as a function of the beam current for the cavity with $L/\lambda = 9.2$. Experimental and theoretical points for the efficiency with and without optimal magnetic profiling are given.

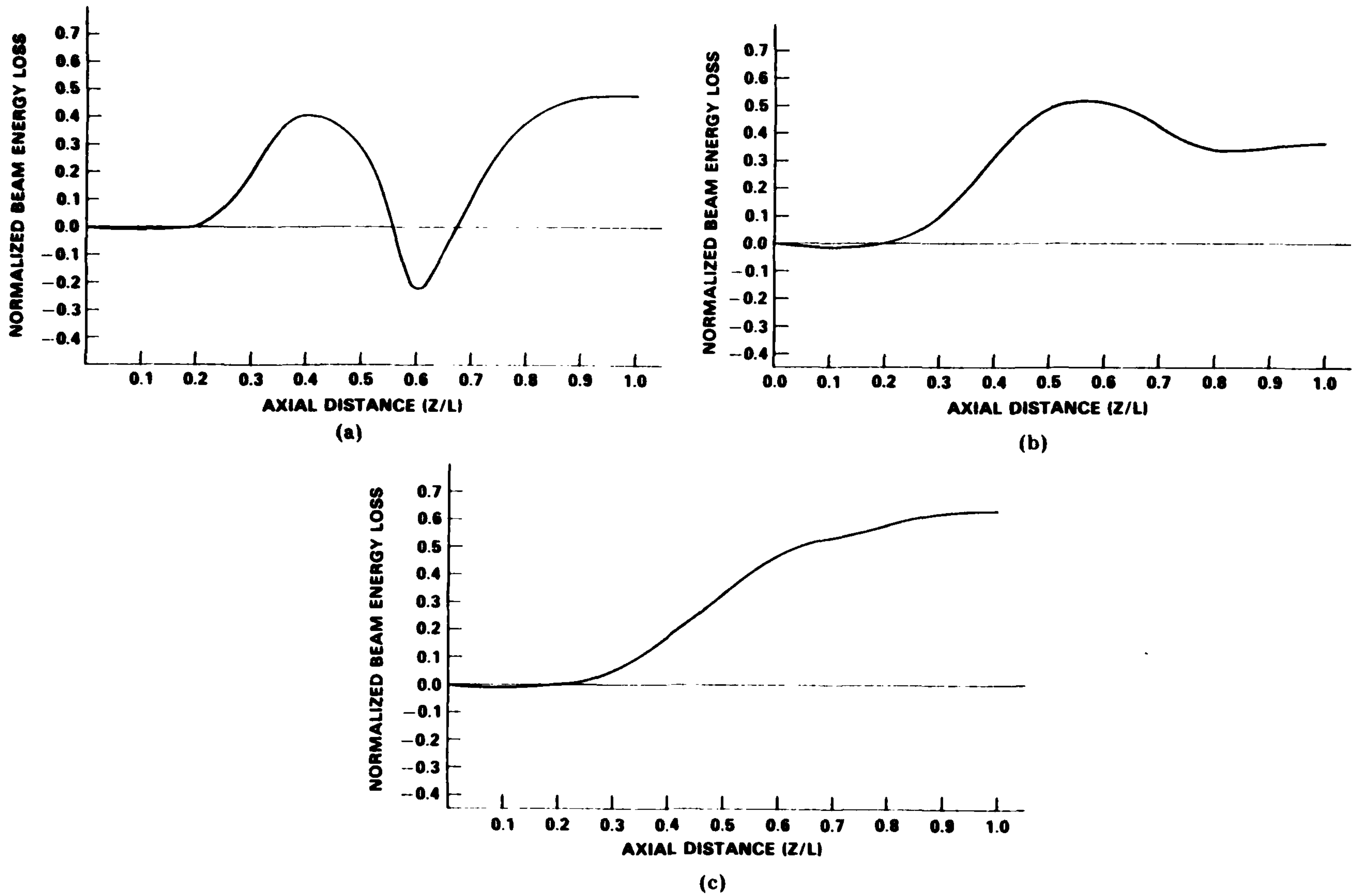

Fig. 6 — Calculated plots of the average energy loss (normalized to the initial energy) of electrons in the beam as they traverse a cavity with $L/\lambda = 9.2$. (a) Beam current = 0.1 amp, (b) I_b = 1.0 amp, and (c) I_b = 1.5 amp. A ratio of the perpendicular to parallel electron velocities of 1.8 was used in the calculations.

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